

## Al Maschke and heavy ion fusion

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### Abstract

It is fitting that this symposium be dedicated to the memory of Al Maschke. His recognition of the implication of the very high  $dE/dx$  of high energy heavy ions in matter was the first connection made between the mature accelerator technology of high energy physics and inertial confinement fusion of DT. Moreover, he contributed many significant ideas to the development of the field. Especially important was the Maschke power transport limit, elucidated in the first workshop. Its implications are discussed. Al's attention then shifted to the front end of the accelerator system and his contributions include application of the Gabor lens, origination of the Meqalac system, resonance crossing and the concept of momentum-rich beams for fusion applications. These contributions are described together with some personal comments and some recollections of the early evolution of heavy ion fusion as background. While some early events are mentioned, this paper is not meant to be an exhaustive history.

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### 1. Some recollections on the early history of the heavy ion fusion concept

Al's initial publication on the subject of inertial fusion of DT dealt with the initiation of thermonuclear detonations in a column of liquid DT by a beam of uranium ions from one or more storage rings [1]. It was the first connection made between the mature accelerator technology of high energy physics and inertial confinement fusion (ICF). The paper was initially classified so that the general accelerator community first learned of it from a post-deadline paper at the Particle Accelerator Conference in Washington, DC, in March 1975 [2]. My initial ideas on inertial confinement fusion using light ion beams were also presented at this conference [3].

In the summer of 1975 Al and I were invited by the Sierra Club to talk about our ideas on inertial fusion at the Sea Ranch in California. Al dis-

cussed accumulation of 100 MJ of  $U^{+}$  at 100 GeV but without detail on sources or injection techniques, while I discussed injection techniques with light ions, particularly non-liouvillian methods. The latter were utilized at Argonne to propose (with Rick Arnold) molecular dissociation of hydrogen iodide with a Doppler-shifted ruby laser to store 1 MJ of iodine at 40 GeV [4]. In the late fall of 1975 Glenn Kuswa in Defence Programs and Bill Herrmannsfeldt in Energy Research at DOE found these ideas sufficiently interesting to organize a 1 day meeting of accelerator and target people at Gaithersburg, Maryland. The meeting took place in February 1976, during which it was decided to hold a 2 week summer study on the topic of heavy ion inertial fusion.

Before the first workshop Dennis Keefe [5] proposed the linear induction accelerator (LIA) for the heavy ion fusion (HIF) application. It was projected that the LIA, given adequate source

current, could accelerate adequate charge in one pass through the accelerator while simultaneously compressing it to the required short time duration and very high power levels for pellet compression and ignition.

The first workshop [6] was held at the Claremont Hotel in Oakland/Berkeley, California, 19–30 July 1976, and several important results emerged. One was that sources of singly charged heavy ions could be built with currents of 50–100 mA and sufficiently low emittance for the purpose. Also initial target requirements were presented by the Livermore group. The maximum range desired called into question the use of such high ion energies as both Al Maschke and Arnold and I were proposing. Lower ion energy would mean more difficulty in achieving the six-dimensional brightness required. The general result of the workshop was very positive, however, and experimental programs were supported at Brookhaven, Argonne and Berkeley Laboratories in 1976.

At the third workshop, at Argonne in 1978, Al Maschke [7] presented a detailed concept for HIF. This employed eight  $U^{1+}$  ion sources of 20 mA each with three stages of funneling (and stripping to  $U^{2+}$ ) to give 160 mA at 20 GeV. This beam was passed through multiplier rings in the horizontal and vertical planes, stored in eight accumulator rings and compressed by five times in the final transport line to deliver 10 MJ of energy with a peak power of 200 TW on target. This concept was rated by a reference design committee [8] at the workshop as having the highest confidence level of four concepts presented.

## 2. The Maschke transport limit

A simple approximation of the ion beam power that could be safely transported in a focusing channel was discussed by Al Maschke at the first HIF workshop and reviewed by Courant [9]. Al's formula was based on the assumption that the beam filled the aperture of a quadrupole focusing channel and that the space charge defocusing forces were about half the av-

erage focusing forces. Even though this was an approximation and no detailed limit was known at the time, it was an extremely useful formulation. It highlighted the need for heavy ions, low charge states, high pole face fields of the quadrupoles and as high an ion energy as could be tolerated from other considerations in order to meet the very high power levels required at the target end of the transport line. It served as a guide to the design of transport systems. Finally it stimulated a great deal of research by many investigators [10] to define this issue in a more precise way. Notable among subsequent efforts are the program carried out at the University of Maryland on the theoretical and experimental study of transport of space-charge-dominated beams and the experimental study at Berkeley of instabilities in the beam as a function of the phase advance per lattice period. As a result we have reached a rather good understanding.

## 3. The Gabor lens

Shortly after the first workshop Al did an about-face and shifted his attention to the front end of the accelerator system for HIF. Some of his important contributions in this area are described in the following paragraphs.

The Gabor lens [11] uses a confined electron cloud in cylindrical geometry to focus an ion beam in both transverse directions. As a result the focusing strength is quite high. Al identified this property as being important to the HIF program, because the magnetic rigidity of low charge state heavy ions from a source is quite high. He initiated an experimental program and his group constructed and operated at least two such lenses. The theory was verified and focal lengths of 13.9 in were achieved in a section 4.5 in long. The experimental results were discussed [12] in the third workshop held at Argonne National Laboratory in 1978. This development was terminated when the Meqalac concept for dealing with low energy beams of high brightness was originated.

#### 4. The Meqalac system

Meqalac is an acronym for a multiple-beam electrostatic-quadrupole focusing linear accelerator. The Meqalac concept [13] grew out of an analysis Al made of the space charge limits for linear accelerators [14]. This analysis showed that the 6D phase space density of a linac is proportional to  $(f^2/\beta^3)(A/Z)$ , where  $f$  is the linac frequency and  $\beta c$  is the ion velocity. High frequencies at low velocities imply small gap lengths, hence small apertures and beam sizes. An array of such beamlets to give adequate current could produce a significantly brighter total beam than the same current with larger aperture, even taking into account the dilution involved with the metal in the array between beam holes. There are many possible applications of this principle and one of them is for singly charged heavy ions for HIF.

Maschke's group [15] at Brookhaven constructed a nine-beam Meqalac and successfully tested it with xenon ions. They achieved 85% of the calculated currents, although the brightness was not measured. The next step was to miniaturize the system and produce a very large number of microbeams with the potential of enhancing the brightness advantages of the Meqalac concept. That step, however, was never carried out.

A four-beam Meqalac accelerating  $\text{He}^+$  was successfully constructed by a collaboration of the University of Frankfurt accelerator group and the FOM University in the Netherlands [16]. A similar principle was also adopted at the Lawrence Berkeley Laboratory for the linear induction accelerator scenario for HIF and a four-beam experiment [17] was successfully carried out.

#### 5. Momentum-rich beams for ICF

This was a concept also originated by Al Maschke [18] and may have grown out of the Meqalac idea of high brightness beams. It consisted of surrounding a spherical ICF chamber with a large number of ion sources and high gradient columns operating at a variable energy between 400 keV and 1 MeV. The beams would

be neutralized in the background plasma and time compression (by a factor of 1000) would occur by time-of-flight. The "mass" of the beam would exceed that of the DT target (gas) and the DT would be compressed and heated to ignition by direct transfer of beam energy to the fuel. The inward momentum is produced by the beam and not by ablation, so that the process is very different than the normal ICF scenario. Al made a strong case that an initial 10 kJ demonstration in a 1 m radius sphere with pellet gains of 0.01–0.1 would answer some of the issues and be a significant step toward larger systems with higher gains. Little has been published about the analysis of the target physics for this concept, so its credibility has not been established, and no such small-scale demonstration has (to my knowledge) been carried out.

#### 6. Resonance crossing

An experiment was carried out by Maschke and others [19] on the AGS on fast bunching of a coasting 200 MeV proton beam to produce a tune shift of 1.9 units. This is 7.5 times the normally projected limit, so that several resonances were crossed, including integral resonances. No beam instability was observed. The result indicates that space charge might not be limiting at injection into a ring. The experiment could not be pursued further, because the next step would be too large a perturbation on the normal operation of the AGS.

#### 7. Personal comments

Al Maschke was one of the more innovative people I have known. His insight was remarkable and he had the broad understanding of physics to be able to work through any new idea to its conclusion. It is a tribute that the people who worked for him appreciated him a great deal and thought that the experience was one of the most exciting periods of their lives.

Al was an unforgettable individual. He held very strong beliefs about life around him as well

as about technical subjects. His conversation was sprinkled with insight, with humor and with occasional pointed barbs. He was at times very animated and the intensity sometimes reached the level of that of a professional dancer, much to the delight of his audience. His colorful description of “popping a pellet” with laser or ion beams will be remembered by everyone who knew him.

The heavy ion fusion community owes him a profound debt.

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